4D Tracking Detectors: Monolithic Fast Timing Silicon Detectors
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Abstract

A new scheme of silicon tracking detector is proposed here for a fast timing detector that provides the 4th dimension of time in addition to precision spacial position. The combination of Low Gain Avalanche Detectors and monolithic readout will advance particle track information and can be used in conjunction with a showering layer to also provide electromagnetic calorimetry. These detector capabilities are expected to enable precision tracking and jet finding in a high pileup regime associated with high luminosity colliders as well as particle separation between neutrons, kaons, and pions in the electromagnetic calorimeter. The work proposed here will establish the physics performance benefits of a 4D detector design; design, fabricate, and test a 4D sensor; and assess the feasibility of a 4D detector at the EIC.

1 Introduction

The charged particle tracking detector is at the heart of every collider experiment. The research proposed here will add a new dimension to the track reconstruction–the time. High luminosity experiments inherently have fast bunch spacing. The current experiments only detect signals within the accuracy of the bunch-crossing window, the shortest of which is 25 ns at the Large Hadron Collider. Adding a time measurement provides a new sensitive dimension for particle measurements.

Breakthroughs in detector technology often enable new capabilities in science. For the EIC these could include better pattern recognition in track finding and new jet finding algorithms that use particle time to identify jet substructure and weed out extraneous noise or pileup contributions, a new method for particle identification in the electromagnetic (EM) calorimeter, or advanced track triggers to increase the acceptance of particular physics signatures. Part of the proposed research plan is to evaluate the possible physics benefits of a 4D detector. These performance improvements will benefit the physics program at either eRHIC or JLEIC. [1]

2 Low Gain Avalanche Detectors

Low Gain Avalanche Detectors (LGADs) present a new direction in silicon sensor technology for high luminosity collider applications that uses a space-time approach to track reconstruction and pattern recognition. [2] These sensors have the unique feature of a highly doped surface region in the $n - p$ junction of the detector that creates a large electric field gradient resulting in increased charge multiplication or gain. [3, 4]. A layer 1-5 μm thick of highly doped material such as boron or gallium with charge density on the order of 10^{16}/cm^3 can achieve an electric field of approximately 300 kV/cm. The electron-hole pairs that are created by an incident particle have enough kinetic energy to create additional electron-hole pairs and create an avalanche effect. These sensors are also sometimes referred to as 'ultra-fast silicon detectors' because the charge multiplication factor enables sensors to collect the signal faster. In general, the collection time is limited by the drift velocity and thickness of the sensor. For a 300 μm thick silicon sensor, the collection time is on the order of 3 ns. If the sensor is thinned, the collection time is reduced, but so is the charge collected, which then degrades the signal to noise ratio. Charge multiplication enables a thinner sensor to be read out. Furthermore, an on-pixel amplifier in a monolithic design may also mitigate the effects of less charge collected as sensors are thinned.

One of the limiting factors in this technology is the noise floor, which limits the timing resolution. The landau noise fluctuations limit the timing resolution to approximately 10-30 ps for 50 μm thick sensors going beyond this barrier (if necessary) may prove challenging. Thinning sensors below 50 μm may enable faster timing resolution if necessary, but the decreased signal to noise will have to be mitigated. As mentioned previously, this could be attempted with an on-pixel amplifier as used in other monolithic silicon devices. Incorporating an amplifier in an LGAD sensor has not been previously attempted and may present technological barriers due to silicon fabrication limitations. Additionally, the radiation tolerance of the sensors may also need to be addressed. Radiation damage results in a change in effective doping concentration–a key element to achieve the charge multiplication effect. Decreases in gain have been observed at 1×10^{14} 1 MeV N$_{eq}$/cm^2 with complete loss in detector sensitivity at 1×10^{15} 1 MeV N$_{eq}$/cm^2. The exact mechanism is not understood, but the proposed materials approach in the R&D program outlined here is equipped to address this challenge.

3 Performance Requirements

The performance requirements necessary to achieve a benefit in physics performance have not been thoroughly evaluated and it remains one of the goals of this proposal. Figure 1 represents a best estimate of what the goals will be for a 4D LGAD detector at the EIC.

	Tracker	EM calorimeter	Best achieved
Pixel size	20-50 μm	1 cm	✔
Time resolution	10-30 ps	10-30 ps	50 ps
Radiation tolerance (N_{eq}/cm^2)	$1x10^{15}$	$1x10^{14}$	$1x10^{14}$
Monolithic design	yes	yes	no

Figure 1: The performance requirements are estimated for a tracking detector and EM calorimeter at the EIC. It is also noted what benchmarks have been already achieved.

4 Pixel Sensor R&D Program

The following research plan will demonstrate the potential of monolithic LGAD technology for use in the EIC. This will require a comprehensive R&D program that will enable an improvement in the design of the LGADs to increase the timing resolution by a factor of 2-5 and demonstrate the radiation hardness for relevant EIC fluences that will be defined. This research program will establish a characterization program that quantifies the detector performance as well as the material properties. The research program will utilize the latest techniques in Material and Nanomaterial Sciences to map the material properties of the crystalline structure and feed this information into simulations. This knowledge will be key to redesign the doping profile in order to manipulate the electric field in the sensor to enhance the collection speeds. An irradiation program is also expected to quantify the defects introduced by particle radiation, design the sensor to mitigate (or take advantage of) these effects, and prove sufficient radiation hardness. Finally, the sensors will be evaluated under test beam conditions to measure the position and timing resolution and to assess the feasibility of the technology for the EIC.

Characterization Measurements
The first step in the monolithic LGAD program is to establish a suite of measurements to fully characterize the sensors. The traditional measurements of current vs. voltage (IV) and capacitance vs. voltage (CV) will be done to determine depletion voltage and breakdown voltage. A radioactive source(s) will be used to measure Charge Collection Efficiency (CCE), signal amplitude, and timing. The output signal pulse can be further characterized by using a laser to stimulate charge in the sensor at specific depths of the sensor. This technique is referred to as the edge Transient Current (Charge) Technique (edge TCT). The possibility of using the Advanced Photon Source (APS) at Argonne to stimulate charge and characterize the output signal will also be investigated. A probe station will be used for small quantities of measurements and a test-bench setup will be developed for automatized measurements. A light-tight cold box will be built with a vacuum chuck to hold the sensor and inlet/outlet for gas and electrical connections, so that measurements can be taken at low temperatures (down to at least -20 degC).

Expertise from the Material Science and Nanomaterial groups at Argonne will be used to measure

the properties of monolithic LGAD sensors using methods such as scanning laser microscopy and spectroscopic techniques. This will enable the direct measurement of the effective doping concentration, types of defects, trapping centers, resistivity, and mobility located throughout the sensor. A detailed geometric layout of the doping profile can then be fed into Sylvaco TCAD simulations that can accurately predict the electric field profile and the response to charged particle radiation. The overall motivation is to gain a deeper understanding of the fundamental principles that drive charge collection performance to make more efficient detector designs.

Irradiations
An irradiation program may include irradiation by protons, neutrons, and gammas. It is important to study the different species because they can cause different defect generation in the sensor and result in different types of changes in performance [5].

Design Cycle
This program covers the complete cycle of R&D and qualification of the monolithic LGAD sensor. There is planned a complete iterations of sensor design, fabrication, and testing. The sensors will be thoroughly characterized, irradiated, and re-characterized with a focus on material properties and the electric field profile. The measurement information will be fed into the simulations. From there, the sensor will be redesigned in the simulation to improve the performance speed. The new design will be implemented in a fabrication process and the work will be hired out. Several companies may be used for the fabrication such as On Semiconductor, TowerJazz, or Novati Tech. The selection will depend on the capabilities to implement the required design. The largest portion of the M&S budget is the wafer procurement. Enough funds are allotted for an assumed multi-wafer project run estimated at $50,000.

Test Beam
The performance of the monolithic LGAD sensor will be evaluated in test beam conditions. A series of sensors will be aligned along the test beam axis to measure position and timing resolution with a known pixel telescope. The test beam setup will require a high precision position of the angle of the detectors to get an accurate reconstruction position and timing resolutions.

Goals
The goal is to assess the feasibility and potential benefit of a 4D detector based on a monolithic LGAD design. The exact timing performance target will be defined, but is expected to be between 10 and 30 ps. The radiation tolerance requirements also need to be defined, but is estimated to be similar to (or slightly less than) the LHC experiments at 1×10^{15} 1 MeV N_{eq}/cm^2. The main challenge once these goals are achieved will be to handle the data such that critical information is not lost.

5   Work Plan Implementation

The proposed work will be carried out at Argonne National Laboratory with the exception of the irradiation and test beam studies. These will be carried out at appropriate facilities such as the Los Alamos Neutron Science Center for proton irradiations, Sandia National Laboratory for neutron and/or gamma irradiations, Fermilab test beam facilities, SLAC test beam facilities, and CERN test beam facilities based on availability. The postdoc will be supervised by the PI and will spend half their time on this project. The graduate student will be supervised jointly by the student's

university supervisor, PI, and postdoc. The test stand will share the laboratory space with the ATLAS Phase II upgrade pixels allowing for shared tools, equipment, and expertise.

The deliverables are outlined below with the corresponding budget shown in Figure 2.

5.1 Deliverables

Year 1

1. Detector Simulation
   - evaluate the impact of a 4D detector on physics performance using fast/full simulation
   - define target timing resolution

2. 4D Sensor Simulation
   - TCAD simulation of monolithic LGAD device

3. 4D Sensor Design
   - design 4D sensor concept for target timing resolution (expected 10-30 ps)

4. 4D Sensor Testing
   - develop laboratory test stand
   - gain experience with existing LGAD devices

Year 2

1. 4D Sensor Design
   - implement design concept to target timing

2. 4D Sensor Fabrication
   - join multi-project wafer run for production

3. 4D Sensor Testing
   - laboratory test stand characterization measurements

Year 3

1. 4D Sensor Testing
   - irradiate and test 4D sensor samples
   - perform test beam measurements with the 4D sensors

2. 4D Sensor Benchmarks
   - assess potential of the technology to meet design targets for EIC
   - define main technological challenges
   - propose solutions

3. 4D Sensor Design (Optional)

- implement solutions in new design

Cost ($k):	Year 1	Year 2	Year 3
postdoc (50%)	65	65	65
graduate student	20	20	20
electrical engineer	20	10	10
mechanical engineer	20	10	10
sensor design	10	50	
multi-project wafer run		50	
materials and supplies	20	10	20
travel	5	5	15
TOTAL	160	220	140

Figure 2: The proposed budget broken down by cost is shown for each year. Year 1 corresponds to the fiscal year FY17 starting in October 2016.

Figure 3 shows the personnel responsible or contributing to each task. In each instance the postdoc or graduate student will carry out the task with guidance from other experts that are indicated. The TCAD expertise is drawn from the x-ray science division at Argonne where similar work is being carried out for silicon detectors for the Advanced Photon Source Upgrade. They are also willing to share their Sylvaco TCAD seat. The detector simulations expert is Sergei Chekanov at ANL, who has performed many similar studies for other future colliders and plans to perform complimentary simulations studies for the EIC. The materials experts are in the Material Science division and Nanoscience and Technology division at ANL.

		PI	postdoc	grad student	EE	ME	Sensor designer	TCAD expert	Simulation expert	Material expert
	Year 1									
Detector Simulation	evaluate the impact of 4D detector on physics performance using fast/full simulation	✔		✔					✔	
	define target timing resolution	✔		✔					✔	
4D Sensor Simulation	TCAD simulation of monolithic LGAD device	✔	✔					✔		
4D Sensor Design	design 4D sensor concept for target timing resolution (expected 10-30 ps)	✔	✔				✔	✔		
4D Sensor Testing	develop laboratory test stand	✔	✔	✔	✔	✔				✔
	gain experience with existing LGAD devices	✔	✔	✔						
	Year 2									
4D Sensor Design	implement design concept to target timing	✔	✔				✔			
4D Sensor Fabrication	join multi-project wafer run for production	✔	✔				✔			
4D Sensor Testing	laboratory test stand characterization measurements	✔		✔	✔	✔				✔
	Year 3									
4D Sensor Testing	irradiate and test 4D sensor samples	✔	✔	✔	✔	✔				
	perform test beam measurements with the 4D sensors	✔	✔	✔	✔	✔				
4D Benchmarks	assess potential of the technology to meet design targets for EIC	✔	✔	✔						
	define main technological challenges	✔	✔	✔						
	propose solutions	✔	✔	✔						
4D Sensor Design (Opti	implement solutions in new design	✔	✔							

Figure 3: The deliverable items are listed with a check mark indicating the people involved in each item. The electrical engineer (EE) and mechanical engineer (ME) are shown.

6   Summary

The proposed research program will investigate the science drivers for a 4D detector at the EIC. It will define the performance requirements necessary to meet physics performance criteria. The main effort will be focussed on evaluating LGAD silicon sensors as as the technology to meet those requirements and outline the feasibility of achieving those targets for the EIC. This will be achieved by thorough device characterization, simulation, design, and fabrication.

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